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Art. XXI.—*The Physiography and Geology of the Bulla-Sydenham Area.*

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[Read 11th December, 1920].

(With Plates XXXII.-XXXIV.)

Contents.

Cartography.

The area examined covers 20 square miles, and takes in the eastern half of quarter-sheet 7 S.E., and the western portion of quarter-sheet 2 S.W. There are neither dates nor compass points on these sheets.

The date of one edition of the quarter-sheet was probably 1863, but the dates of the other two editions could not be obtained. Two different copies can be seen at the Melbourne Public Library, and a third at the Geological Survey Department. One of the three editions has the Silurian conglomerate south-west of Hanging Valley (Plate XXXII.) wrongly coloured as Kainozoic.

The dips and strikes of the palaeozoic rocks on the quarter-sheet are inaccurate.

In the three editions of quarter-sheet 7 S.E., a large heart-shaped area of tree covered granite, south of Bulla, is wrongly coloured as basaltic.

In the military contour map of Sunbury two errors in road marking occur. In the extreme N.E. of the area the formed road L M (Plate XXXII.) is omitted, while the road N O in the centre west is shown as continuous across the gorge, which is called in this paper, "Column Gully."

The granodiorite boundaries in the N.E. cannot be accurately placed, owing to the gravitation of granitic detritus from the hills. It covers the lower lying basalt, and hides the junction.

Owing to the great accumulation of hill wash along the streams many outcrops are completely covered. This is probably the reason why two conglomerates marked on quarter sheet 7 S.E. are not now visible.

Attention is drawn to the names of the streams in this area, and a study of the geological quarter-sheets, the military contour maps, and the parish plans shows how loose the nomenclature has been. The names of the streams in the parish plans of 1901 differ from those of 1916, and as the names of the latter agree with those given by the local residents, the writer has accepted them for this paper. The eastern branch is Deep Creek, the western branch Jackson's Creek, and the Maribyrnong River (formerly Saltwater River); the stream from the junction of the creeks to the Yarra. The following is a table of the names given to the streams in this area in old and recent publications:—

Publication.	Western Branch.	Eastern Branch.	Combined Creeks.
Geological quarter sheet, 1863	Macedon or Saltwater River	Deep Creek	Saltwater River
Parish Plans, 1901	Saltwater River	Deep Creek	Saltwater River
,, ,, 1616	Jackson's Creek	Deep Creek	Maribyrnong River
Military Contour map, 1917	Jackson's Creek	Maribyrnong River	Maribyrnong River
Donald Macdonald in *Argus*, 22/4/19	Jackson's Creek	Deep Creek	Deep Creek above tidal water. Maribyrnong River below tidal water.
Residents and nomenclature followed by writer 1919	Jackson's Creek	Deep Creek	Maribyrnong River.

Physiography.

General Survey.—The dominating feature of the area is the great basalt sheet which slopes gently from the north-west to the south-east, with a slope of 60 ft. per mile, descending from 600 ft. to 300 ft. in five miles. The Deep Creek, Jackson's Creek, and the Maribyrnong River have entrenched themselves in this low plateau to a depth of 300 ft., and they are vigorous young streams, cutting deeper and deeper into a plain that is also very youthful in character. Two granodiorite masses rise 100 feet above the lava surface.

Meanders.—Deep Creek, Jackson's Creek, and the Maribyrnong River meander in a trench about 300 ft. in depth. These streams originally flowed on the surface of the basalt plain, and the slight curves in their old courses became more and more pronounced as the streams deepened their beds. While lateral erosion was at work deepening the curves, vertical corrosion was deepening the valley, and this combined action has resulted in an alternating series of spurs and river cliffs along each stream. Waterworn pebbles of basalt, quartz, quartzite, etc., along each spur, afford evidence of the former position of the stream. This type of meander is in sharp contrast to the flood-plain meander, where only lateral erosion is active.

Several writers (1) describe an entrenched meander as one where the original meander has been preserved, and where the opposite banks of the stream make approximately equal angles with the surface of the ground. According to these geographers, the spurred meanders of Bulla and Sydenham would not be entrenched meanders. W. M. Davis, however, refers to the spurred character of the entrenched meanders of the Meuse and Seine. (2b) It is important to note that the present meanders of Deep Creek are not simply the preserved meanders of the old stream, as indicated by J. W. Gregory (3). The length of the present curves is very much greater than that of the old curves, owing to the lateral swinging of the streams, but the radii of the curves have remained approximately the same, (2a).

Down-valley Sweep of Meanders.—This sweeping movement is not so pronounced as in streams flowing through soft rock, but the effect can be definitely seen in most of the spurs along either creek and in the position of the small flood plains. The spurs are not symmetrical in section, the steeper side always pointing up-valley. This also has the effect of sharpening the spur, and the placing of the flood plain, not at the end of the spur, but on the down-valley side of it. (2a.)

Meander Belt.—In youthful streams, such as Deep Creek, the belt of wandering and the meander belt coincide with one another. The stream by lateral swinging widens its meander belt, but this tendency is checked by (a) the down-valley sweep of the meanders (which would eventually cut through the spurs), and by (b) the formation of new channels at flood time across low spurs.

Relation between Radius of Meander and Volume of Water.—W. M. Davis has shown (2a and 9), that the radius of a meander, where slope and load are equal, is proportional to the volume of water. This is exemplified in Jackson's Creek, Deep Creek and the Maribyrnong River. Jackson's Creek has a slightly smaller volume than Deep Creek, and the radii of its meanders are slightly smaller than those of Deep Creek. Similarly the radii of the Maribyrnong meanders are considerably larger than those of the creeks.

Hanging Valleys.—Excellent examples of hanging valleys are found along both Jackson's Creek and Deep Creek. In every case these tributary streams flow only after heavy rain. The best example is that to the south-west of the main granodiorite outcrop. This small stream has been formed along the junction of the basalt, and the granodiorite. At its junction with Deep Creek there is a fall 80 ft. in height. Owing to their poor supply of water the tributary streams are unable to corrode their beds as rapidly as the main streams. This is the chief cause of the lack of adjustment between the tributaries and the main streams in this area. At Hanging Valley (see Z, Plate XXXII.), this lack of adjustment is increased by the hard compact hornfels in its lower course.

Deserted Bed of Jackson's Creek.—An old accumulation of boulders can be seen in the right bank of the Maribyrnong River, a quarter of a mile south of the junction of the creeks. Some of the boulders are huge, some small, some of basalt, some of conglomerate, and others of sandstone, but none of granodiorite. It was the old bed of Jackson's Creek which deserted it when it flowed 6 ft. above its present level. If Deep Creek had contributed boulders to the conglomerate, granodiorite also would have been represented.

Corrosion.—A study of the effect of the volcanoes on that section of Jackson's Creek north of Sunbury would provide interesting matter, for it is evident that the Sunbury volcanoes in late Kainozoic times, formed an immense bar across the old Jackson's Creek, and overwhelmed the valleys to the south beneath a flood of lava.

It will be noticed that Deep Creek flows close to the boundary of the granodiorite, and the basalt. Originally it flowed along the junction. As Deep Creek deepened its bed, the granodiorite became exposed on both banks. It is probable that streams such as the Yarra and Deep Creek tend to flow at the junction of basalt and older rock because hill drainage helps to form a valley at the junction of the bedrock, and the lava sheet, and because the lava flow is probably depressed at the edges, and thus directs the drainage of the area to the line of junction.

By meandering and deepening the streams have reduced the slope from 60 ft. per mile to 18 ft. per mile. From the creek junction to the most northerly point of Deep Creek, marked on the map, is 7 miles. In this distance it falls from 280 ft. to 150 ft., giving a slope of 18 ft. per mile. It is remarkable that Jackson's Creek from the north-west boundary on the map to the creek junction flows 11 miles, and falls from 350 ft. to 150 ft., giving again a slope of 18 ft. per mile. The slopes are interesting when compared with that of the sluggish Mississippi, which has a fall of less than 1 ft. per mile. At the Bulla School the creeks are only half a mile apart, but, owing to the short distance along Deep Creek to the junction as compared with that along Jackson's Creek, the bed of Deep Creek is 60 ft. lower than that of Jackson's Creek. This illustrates the fact that in river capture the more vigorous stream may be captured by the less vigorous. Jackson's Creek and Deep Creek having the same slope, are of equal vigour, but if their valleys met Deep Creek would capture the head waters of Jackson's Creek.

Deep Creek has been superimposed along the whole of its course on the older rocks beneath. Jackson's Creek is still cutting into basalt, though it frequently carves its way across the tops of the old Ordovician and Silurian hills.

Basalt bars of greater density retard its rate of deepening by checking its velocity. In several parts Jackson's Creek resembles a series of small lakes separated from one another by basalt bars over which the water tumbles in miniature rapids.

Headward Erosion.—The extremely youthful tributary streams frequently become gorge-like, and tend to cut back across the fields. Farmers in this locality meet the problem by piling boulders at the head of the tributary and planting hardy shrubs around them in order to check the velocity of the water, and thus retard the transport of material. The early neglect to check the headward erosion of youthful streams has led elsewhere to great loss of land. A large area at Coburg has been rendered unfit for habitation within the last thirty years, and the same will occur at Aberfeldie, near the Essendon sand pits, if preventive measures are not taken soon.

Near the school at Bulla an extremely young active tributary has cut back from Deep Creek and formed a canyon in decomposed granodiorite and basalt. Apparently no effort has been made to check the headward erosion, and now it is completely out of hand, and threatens the roads north of Bulla. The canyon is about 60 ft. in depth. It is not likely to deepen further for many years, as its floor is nearly adjusted to the present level of Deep Creek. Lateral erosion is now rapidly increasing the area of destruction.

Basalt Outliers.—A small outlier is seen in the south of the large granodiorite outcrop, and another in the extreme centre-north in Ordovician sediments. They represent small basalt tongues that have been cut off from the main lava sheet by river action.

Palaeozoic Rocks.

General Description.—The bedrock of the area so far as is known consists of Upper Ordovician and Lower Silurian sediments in the form of shales, sandstones, conglomerates, quartzites, slates and hornfels. These have been strongly folded by approximately east and west pressure, and the prevalence of easterly dips suggests overfolding to the west. The folds pitch to the north, and this pitch makes the strike of the strata somewhat irregular.

Throughout the district these palaeozoic rocks have been highly fractured and faulted, most of the faults being reverse strike faults. On the left bank of Deep Creek, at the mouth of Hanging Valley, is a fault breccia altered to hornfels by the granodiorite intrusion.

If the conglomerate (C_3), near Hanging Valley, and conglomerate C_1 or C_2 on Jackson's Creek, be parts of the same stratum, lateral displacement must have taken place, and, though this is the probable explanation, yet local lenticular accumulations of conglomerate may be the reason why these bands do not appear on the same line of strike. Owing to intense pressure, well defined joint planes have been set up which tend to break the strata into small rhombohedra. These joint planes give difficulty in the taking of dips and strikes, as they closely simulate the bedding planes.

Palaeozoic Fossils.—Previous to 1918, Upper Ordovician graptolites had been found in the extreme north-west of this area (4), while Lower Silurian graptolites had been found in the extreme south-east (5), but none had been found between these localities.

In 1917 and 1918 the writer came across several fossil beds whose position is indicated on Plate XXXII. The paucity of fossils in this locality is probably due partly to dynamic and thermal metamorphism, which prevent the rock splitting along the bedding plane, and partly to the sandy nature of the sediments.

It has been suggested that the conglomerate C_1 is of glacial origin, and the absence of fossils in this neighbourhood is due to the severe climatic conditions that prevailed during their deposition. (6.) Fossils have, however, now been found in the following localities:—

(a) On the left bank of Jackson's Creek, 50 yards north of the mouth of Column Gully. (See Plate XXXII.) In a very narrow band Upper Ordovician graptolites can be obtained in abundance, Coenograptus and Diplograptus being the commonest genera. The fossils are well preserved, but are rapidly obliterated on exposure to the air.

(b) On the left bank of Jackson's Creek, half a mile south-east of the Organ Pipes. For nearly a mile along both banks of the creek, the rocks contain enormous numbers of worm impressions. On the rock face a few yards south-east of dyke D_6, the markings strongly suggest worm burrows, but Mr. F. Chapman says that they are probably the remains of the soft part of the worms. The impressions are quite different from those of Trachyderma (7). From the graptolite bed referred to in (a) to the conglomerate C_1, these impressions occur in varying numbers. The upper part of each stratum has more impressions than the lower part, and many of the most prominent markings are perpendicular to the bedding plane, and increase in diameter from below upwards.

Mr. F. Chapman has not been able to determine the age of these worms, but as there is field evidence that they are of Ordovician age, they will be called tentatively in this paper the "Ordovician worm beds."

(c) On the right bank of Jackson's Creek, at the mouth of a small gully, 30 yards east of conglomerate C_1. Here impressions of the gill plumes of the worm Trachyderma sp. occur in two very narrow bands.

(d) The best impressions of Trachyderma were found on the right bank, about 300 yards down stream from the conglomerate C_1. At this spot Trachyderma and Monograptus were obtained on the same slab. Many of the strata here yield the tubes and gill plumes of this worm, which Mr. F. Chapman has connected with the gill plumes found at South Yarra in Lower Silurian rocks. (7).

(e) On the right bank of Jackson's Creek, 30 yards north-east of the dyke D_3 (Plate XXXII). The writer found three or four species of Silurian graptolites. Graptolites from localities (d) and (e) were sent to Mr. F. Chapman. They have not been named yet, but were pronounced to be definitely Silurian.

(f) At the point x (Plate XXXII.), fossils were found about 1862 (4), by members of the Geological Survey. Mr. F. Chapman has stated that these fossils are definitely Silurian.

Junction of the Upper Ordovician and Lower Silurian.—Previous to 1918 the junction between the Silurian and the Ordovician rocks had been placed one mile S.S.E. of the junction of the creeks (6). As neither unconformity nor fossils had been found, geologists were forced to rely on the study of dips and strikes, and on this evidence alone the placing of the junction there seems to have been justified, for there the dips become lower and the direction of the strike is slightly altered. In this area it is not safe to put too much reliance on variation in strike and dip, because these are much disturbed by faulting, pitching and hill creep.

Two of the three editions of the geological quarter sheet No. 7 S.E., show the Ordovician rocks extending to the S.E. margin, while quarter-sheet No. 2 S.W. shows Silurian extending to the S.W. margin, thus making the edges of the sheets coincide with the junction between the Ordovician and Silurian sediments. A third edition of the quarter sheet 7 S.E., places the junction one-eighth of a mile to the west of this, and this is approximately the line found independently by T. S. Hart (6).

The presence of Silurian graptolites in two localities one and a-half miles west of this junction, and in another one and a-half miles N.N.W., strongly suggests that the junction shown in the quarter sheets is incorrect. There is of course the possibility that the later Silurian rocks occupy an infolded pocket of the Ordovician. In either case we are forced to look for the junction further upstream. It seems to the writer probable that the western face of conglomerate C_1 is the junction. The reasons for putting it there are as follow:—

(a) The junction is necessarily between dyke D_3 and Column Gully, for at the former, Silurian graptolites and worms are found, and at the latter, Ordovician graptolites. These two places are approximately one and a-half miles apart. No conclusive evidence is given by the dips and strikes, for though slight variations occur, up-stream and down-stream similar variations can be noted. In the Ordovician graptolite bed the dip is 84 E. and the strike exactly north and south, while in the Silurian graptolite beds the dip is 77 E. and the strike 8° west of north. Between these two beds there is no sudden change of dip or strike.

(b) The Silurian worm Trachyderma can be found in many of the strata east of C_1, but not west of it,

(c) "Ordovician worm impressions" are found in enormous numbers, from the Ordovician graptolite beds, where they are associated with Diplograptus, right up to the conglomerate C_1, but neither in it nor on the east side. The fact that these marks suddenly cease at the conglomerate strongly suggests discontinuity of conditions.

(d) The conglomerate itself is strictly conformable with the strata on the eastern side, but on the western the contact is very irregular. The one drawback to the placing of the junction at C_1 is the presence of a few pebbles in the strata on the up-stream side of the conglomerate. This suggests similarity of conditions, and though their presence is not fatal, yet it makes one hesitate to accept C_1 as a basal conglomerate.

Palaeozoic Conglomerates.—The four palaeozoic conglomerates in this area have been carefully described by T. S. Hart (5). C_4, the most northerly, is wrongly coloured tertiary in one of the three quarter sheets. It has been pointed out (6) that this conglomerate has been so indurated by thermal metamphorism that the matrix is as hard as the old quartzite pebbles, and thus the pebbles do not weather out.

The southern exposure C_3 can be picked up in a runnel on the cliff about 80 ft. above the stream. It is not altered to the extent that C_4 is.

C_2 shows the clay bands much distorted by differential pressure, as they are in the Italian Cutting, Daylesford (8).

C_1 is the largest of the four conglomerates.

T. S. Hart (6) puts forward various reasons for considering it an Ordovician glacial conglomerate. His conclusions appear incorrect. The following is a summary of the reasons given on which he based his conclusion:—

(1) A part of the conglomerate is a mixture of pebbles and fine clay.
(2) The strata are much disturbed in places.
(3) The matrix is angular.
(4) Some pebbles are facetted and striated.
(5) Fossils are absent on account of severity of the climate at that period.

The writer carefully weighed these points, but was forced to discard the theory of the glacial origin. A mixture of pebbles and clay can be formed in other ways than by glacial action, and the disturbance of the strata appears to be the unconformable junction of the Ordovician and Silurian. The presence of the striations on an insignificant percentage of the pebbles can be accounted for by the fact that when conglomerate bands are folded under pressure, the hard pebbles grind against and scratch one another. Facetted pebbles were not common in this conglomerate, and there was quite as large a percentage in the river conglomerate as in the ancient collection. On examining under the miscroscope, the matrix from conglomerate C_1, and comparing it with material taken from other strata, it did not appear to be more angular than the latter. It has been shown[1] already that life was abundant in the seas in that age.

The direct evidence against this glacial theory is:—

(a) The general linear arrangement of the pebbles.

(b) In C. the pebbles lie regularly on their flat faces.
(c) Pebbly, sandy and clay bands alternate.
(d) Most of the stones are small. Not one large stone is seen. If it were glacial you would expect to find some boulders.
(e) Facetted and striated pebbles are extremely rare.
(f) Many strata contain pebbles of only one size.
(g) The conglomerate is almost certainly of Silurian age, and no other evidence of Silurian glaciation has been reported in Australia.

For the reasons above it seems more likely that the conglomerate C_1 is the basal conglomerate of the Silurian rather than an Ordovician glacial deposit.

The material of which the pebbles are composed is similar to that of the Kerri conglomerate found along Conglomerate Creek, near Macedon (10). There are quartz, quartzite, black chert, quartz porphyry, greisen and diabase pebbles. The Kerri conglomerate contains a large percentage of dimpled and squeezed pebbles, whose state it has been shown is probably due to solution under pressure (10). Many similar pebbles are found in C_1 but most of the dimples have not been made in situ, for frequently the dimples are opposed not to a pebble, but to the clay matrix. A few of the dimples may have been made in situ.

Metamorphic Rocks.

These are exposed along Deep Creek to the north, west, and south of the granodiorite. At and near the junction the sediments have been converted into hornfels, while further away they occur as spotted shales, or as indurated sandstones or shales. The width of the aureole varies considerably, probably owing to the irregular junction of the granodiorite, with the sediments beneath the surface. As far as can be judged from the bedrock exposed along the creeks the hornfels belt on the average appears to be about a quarter of a mile wide, and it gradually merges into spotted slate, which is not uniform in its distribution. The indurated sediments have abundant secondary mica.

In the hand hornfels is a hard, dense, dark rock, in which individual crystals cannot be seen with the naked eye. Under the miscroscope, however, it is seen to have abundant secondary brown biotite. Near the contact there is a considerable amount of cordierite produced, but further away andalusite, biotite, and secondary quartz predominate. The cordierite can be distinguished from the quartz by its cleavage, which is easily picked out, and by the numerous and characteristic inclusions. A little tourmaline is found in a few sections, but secondary quartz is present in abundance in all.

The hornfels close to the contact is very much coarser than that some distance away.

Owing to the quantity of sandstone which characterises the palaeozoic rocks of this area, a considerable amount of quartzite has been formed, much of it being thermal metamorphic in type.

It is interesting to note the difference between the action of running water and the weather on these metamorphosed sediments. They appear to be highly resistant to the latter, but readily succumb to the former, owing to the presence of three sets of joint planes, which divide the rocks into variously shaped rhombohedra. The result is that the stream in flood can break out the rhombs and thus deepen its bed, whereas the ordinary atmospheric agents are not so successful. The importance of jointing is shown near Hanging Valley, where a metamorphosed fault rock of the same material as the hornfels around it has more sucessfully resisted destruction by Deep Creek. The fault rock is not jointed, and the normal hornfels is, thus enabling the stream to remove it block by block.

Granodiorite.

Six outcrops are mapped, three large and three small, and they roughly form a ring round Bulla. The boundary of the north-east outcrop is hidden by later detritus, that has gravitated down from the east. The five outcrops to the north stood out as islands in the lava flood, but the most southerly was overwhelmed by it.

Chemical Character.—The material for analysis was obtained from fresh rock that had been "plug and feathered" on the main outcrop southwest of Bulla.

It was analysed by Mr. F. Watson, and the analysis is given in the following table, together with analyses of other similar rocks for comparison :—

	Granodiorite Hesket	G'diorite Pory Barringa Ck.	Granodiorite Harcourt	Granodiorite Bulla	Adamellite Ingliston	Adamellite Trawool	Adamellite Mt. Gellibrand
SiO_2	68.92	71.65	70-91	**66.13**	71.57	69.19	67.75
Al_2O_3	15.26	14.56	13.99	**16.83**	13.58	13.45	16.11
Fe_2O_3	.80	1.13	.35	**1.11**	1.18	2.71	.50
FeO	3.30	1.56	3.02	**4.17**	2.19	2.78	4.00
MgO	1.64	.84	.80	**1.83**	1.07	1.06	.79
CaO	3.04	1.27	2.35	**3.26**	1.72	2.04	2.68
Na_2O	2.71	2.76	3.94	**2.25**	2.79	2.89	2.60
K_2O	2.93	4.14	3.66	**3.14**	4.36	3.94	3.42
H_2O + 110	1.04	.15	.21	**1.68**	.69	.77	.96
H_2O − 110	.22	1.20	.11	**.23**	.11	.16	.20
CO_2	Nil	Nil	Nil	**Tr.**	.29	.07	Nil
TiO_2	.70	.35	.58	**Tr.**	.46	.51	.85
P_2O_5	.19	.12	Tr.	**Tr.**	.11	.18	.09
MnO	Tr.	.04	Nil	**.07**	.09	.14	Tr
Li_2O	Tr.	Tr.	—	—	Tr.	Tr.	—
Cl	Nil	Tr.	—	**Tr.**	Tr.	Tr.	—
Total	100.75	99.77	99.95	**100.70**	100.21	99.89	99.95
S.G.	2.688	2.630	—	**2.677**	2.655	2.666	2.68
	Mines Dept.	Mines Dept.	G. Ampt.	**F. Watson** 1918	A. G. Hall	A. G. Hall	H. C. Richards

The rather high CaO content, and the relatively low K_2O content of the Bulla rock favours granodiorite rather than adamellite, and the miscroscopical examination confirms this determination.

Megascopic Character.—It is a rather coarse grained, grey rock with many crystals, 10 mm. in diameter. Quartz, plagioclase, orthoclase, biotite and a little pyrite can be seen. The quartz has a greasy lustre, and the felspar tends to be greenish. The rock takes a fine polish, though the coarse biotite is inclined to give the surface a chipped appearance. Basic segregations with their rounded outlines are very common. The specific gravity of fresh rock is 2.677, and thus in keeping with its determination as granodiorite.

Microscopic Character.—It is a non-porphyritic, hypidiomorphic, holocrystalline rock with crystals of various sizes. It is medium to coarse in grain, with a rich assortment of minerals.

The following are present in order of decreasing abundance:— Andesine, quartz, orthoclase, biotite, chlorite, sericite, muscovite, apatite, pyrite, magnetite, arsenopyrite, calcite and zircon. The chlorite, sericite, pyrite, calcite, and arsenopyrite are secondary.

The extinction angles of the carlsbad and the lamellar twins disclose the fact that the plagioclase is basic andesine. Zoned crystals are very abundant, and the zones are seen to be more basic as the centre is approached. Certain bands of the zoned felspars were sericitized before the others, showing that felspars of that composition were not so stable in the presence of sericitizing agents. Generally sericitization took place from the centre outwards, i.e., from the basic to the acid plagioclases. In the sections studied sericite in its turn tends to be kaolinized.

Summary.—The rock from its chemical and mineral composition and its physical properties is a slightly altered granodiorite. In the hand it appears fresh, and shows no sign of weathering.

In the field it undoubtedly appears to be linked to the Gellibrand mass, which has been described by Dr. F. Stillwell as adamellite (11). Both are 500 ft. high, and have the same mineral composition, and approximately the same chemical composition. It differs from the Gellibrand stock in having a slightly higher lime content, and slightly lower silica content.

Dr. F. Stillwell found that the proportion of plagioclase to orthoclase was less than 2:1 in the Gellibrand stock, but the writer by the Rosival method found the proportion distinctly more than 2:1 in the Bulla stock, which is adjacent to it. Slight differences in mineral and chemical composition are probably local, for the two rocks are similar in all other important characters.

Granitic Intrusions.—Near Hanging Valley is a granitic dyke 20 feet wide, intruding the hornfels. Near the southern edge of the main granitic mass there are several small dykes of microgranite intruding granodiorite, while north of Bulla bridge there is a dyke of aplite and a small one of quartz, both in granodiorite.

The dyke near Hanging Valley is evidently a tongue from the main mass, but the microgranite, aplite and quartz tongues appear to have been derived from the acid residue of the magma after the outside portion had cooled and hardened. The magma evidently stoped the palaeozoic sediments so quietly that the dip and the strike are not only unaltered up to the southern contact, but are continued at the northern junction. The sediments to the west also are undisturbed.

A large number of angular and irregular rock blocks are found embedded in the granodiorite along Deep Creek, S.W. of Bulla. That they were originally blocks of sediment that were displaced by the stoping, and then sank into the molten magma, might be inferred by the angularity of the blocks, and by their close similarity to hornfels. If they were basic segregations, you would expect the outlines to be rounded.

Economics.—The best granodiorite for building purposes lies between the deep trenches of Jackson's Creek and Deep Creek, at the 500 ft. level. The expense of hauling blocks of granodiorite across these deep trenches and thence to Melbourne practically prohibits the use of this rock as a building stone.

The granodiorite, in striking contrast to the basalt of this area, is always tree-covered, and with the exception of the trees in the deep creek trenches, is the only local source of timber.

Kaolinized Granodiorite.

Location.—The granodiorite at several places round Bulla and Broadmeadows has been kaolinized. In the area under discussion there are four extensive masses of kaolinized granodiorite, and several smaller outcrops. Two of the large outcrops are being worked by Cornwells for their Brunswick pottery. The others have not yet been opened up.

Description.—At the quarry Q^1 (Plate XXXII.) one can trace the change from hard granodiorite, through the partly decomposed to the thoroughly decomposed and whitened rock. Decomposed basic segregations can also be seen in the face. Much of the mass is left the purest white by the leaching out of the iron oxide derived from the magnetite, pyrite, biotite and chlorite. In other parts the decomposed rock is deeply stained and cemented by the concentration of iron oxide.

In the smaller quarry (Q_2) near the Bulla school, there is a well-marked vein one inch thick, of bluish tourmaline and granular quartz, in a joint plane of the kaolinized granodiorite. Another vein 1½ inches thick has lately been cut out of the kaolin in Q_1.

The quartz granules of the original granodiorite persist, apparently unaltered, throughout the kaolinized mass.

Microscopic Examination.—Angular quartz is surrounded by crystallised kaolin, which appears chiefly as twinned lamellae, though often in the form of scales and aggregates. A considerable amount of sericite is still present, with earthy calcite and zircons.

Origin of the Bulla Kaolin.—Granodiorite may be kaolinized by the action of meteoric water carrying carbon dioxide in solution, which penetrating the granodiorite decomposes the biotite and felspars. Kaolin in Fiji and the Dublin Mts (Ireland) is stated by Prof. Sollas to have been formed in this way (12).

Probably a commoner process of kaolinization and the proved origin of the vast kaolin masses of England and United States (12 and 13) is that of pneumatolysis, where emanations of carbon dioxide, boron, fluorine, or chlorine, probably with steam, have decomposed the felspars and biotite of the plutonic rock.

Three investigators, E. J. Dunn, 1899 (15), R. W. Armitage, 1911 (14), and F. Stillwell, 1911 (11), have briefly discussed the Bulla kaolin. While both Mr. Armitage and Dr. Stillwell refer to the possibility of either surface water or pneumatolysis being the cause of the kaolinization of the Bulla granodiorite, the former favours the meteoric origin and the latter the pneumatolytic origin.

For the following reasons, it seems probable that pneumatolysis and not meteoric water is responsible for the kaolin of this area.

Evidence Against the Meteoric Theory.

(a) Only Isolated Outcrops Occur in Victoria.—This is strongly against the meteoric theory, for if the water and carbon dioxide were subaerial one would expect kaolin to be found in all parts of Victoria, where the old granitic surface is protected from denudation.

(b) Only Isolated Outcrops Occur at Bulla.—There are about ten outcrops at Bulla, and these are separated from one another by solid, unaltered granodiorite. Generally the surface of the granodiorite is protected by basalt and gritstone, and yet only relatively small outcrops of kaolin are found.

(c) Relation of Kaolin to the Sites of Old Valleys.—It has been stated (14) that the Bulla kaolin always underlies basalt which is situated in the sites of old pre-basaltic valleys, and that the drainage beneath and through the basalt would thus tend to be gathered along lines where it could attack the granodiorite vigorously.

In reply to this it can be stated that kaolin does not always underlie the basalt. In the largest Bulla quarry, Q_1, the kaolin is overlain by a considerable thickness of grits. The presence generally of basalt over kaolin is only what one would expect. Suppose a granodiorite mass had been converted into kaolin at various places by pneumatolysis long before the lava floods. At these places the weathering would be much more rapid than where the rock was unattacked. Depressions would be made, and, later, occupied by the lava, while the fresh and less denuded rock would stand up as a monadnock above the molten basalt.

(d) Fresh Granodiorite under Basalt.—In two places fresh, hard granodiorite was seen directly beneath basalt at a low level, while the granodiorite to the side of it had been kaolinized. At another place granodiorite was seen under basalt that had flowed into an old valley. There was no sign of kaolinization.

(e) Shape of the Outcrops.—In this area the shape of the outcrops is not very definite, but where it is shown it agrees with type (a), (Fig. 1, Plate XXXIII.) If the kaolin were of meteoric origin, it would be of type (b) (Fig. 2, Plate XXXIII.).

(f) Relation of Kaolin to Depth.—In every case the rock near the bottom of an outcrop is as much altered as that higher up the face. If the decomposition were due to surface water and carbon dioxide, then decomposition should decrease as the depth increased, for the solid rock deep under the surface stream would suffer very little from downward drainage.

(g) No Evidence of Stream Beds above the Kaolin.—If the kaolin were formed by water in old valleys draining through granodiorite, some trace of stream material above the kaolin would very likely be found. No trace of river gravels, silt or conglomerate was found above any of the kaolin masses.

(h) Kaolin Found at Many Levels.—Kaolin can be found right from the level of the stream to 200 ft. above it. One would not expect such differences in level in separated outcrops if old valley floors determined the point of attack on the granodiorite by the stream water with carbon dioxide in solution.

(i) No Evidence of Kaolin Being Formed in Present Stream.—The granodiorite along Deep Creek and on the hill sides is not kaolinized. If kaolinization be due to subaerial agencies, why has not the granodiorite in this stream bed been kaolinized?

(j) Accompanying Minerals.—Kaolinization by pneumatolysis is generally accompanied by the production of tourmaline, fluor, cassiterite or topaz, which cannot be produced by subaerial agents. A vein of tourmaline in Q_1 and another in Q_2 (Plate XXXII.) give valuable positive evidence that magmatic vapours have been present to some extent at least.

Summary.—The microscopic examination of the kaolin gives no definite evidence in favour of either theory, but the field evidence, while producing little positive evidence in support of pneumatolysis, strongly discounts the meteoric theory. The fact that no fluor, cassiterite, or topaz is found in the kaolinized rock, and only a small amount of tourmaline, rather suggests that we must turn to magmatic water and carbon dioxide as the agents causing kaolinization, as in Cornwall and in the United States (12). The earthy calcite in the sections of the kaolin supports this conclusion.

Economics.—Fifty years ago a company was formed to export this material to England, where it was bought at 18/- per ton. Owing to the heavy transport cost the company failed.

At present the kaolin in Q_1 and Q_2 is being worked by Cornwells, who use it for making fire bricks and other articles used at high temperatures. There is a growing export trade in these manufactured articles.

On account of the trace of iron in the Bulla kaolin, it has not, up to the present, been used for chinaware. The quantity of kaolin appears to be unlimited.

Kainozoic Rocks.

Older Basalt.—In the south-east of the area three lenticular outcrops were found. The most northerly is vesicular, and rests directly on Silurian sediments, and underlies a very thick cap of stratified Kainozoic grits. The best section, however, is seen in a cliff face in the extreme south-east, where very decomposed older basalt overlies a pre-older basaltic river conglomerate, about 8 ft. in thickness, which merges into sands at the sides. This sand and the sandstone conglomerate beneath the basalt are strictly local in origin, and remind one very much of the sands underlying and overlying the leaf beds two and a-half miles to the N.N.W.

In this decomposed basalt there are, in situ, several undecomposed basaltic nodules. These remove all doubt as to the identity of the outcrop. The basalt thins out at the edges, and here the underlying sand has in part been altered to quartzite, and the overlying sandy clay to a rock resembling red brick. Newer basalt more than 100 feet in thickness rests on these beds.

Pre-older-basalt River Valley.—The alignment of the three southern outcrops is indicative of an old river valley, and this conclusion is upheld by the presence of a conglomerate in the southern exposure.

No evidence of stream action in the two patches to the north was found, but this may have been hidden by the talus, which masks the surface. The northern outcrops are at a lower level than the southern one, and this suggests that the stream in this locality flowed to the N.N.E.

Basic Hypabyssal Rocks.

Along Jackson's Creek, in the south of the area, there occur at least seven basic to ultrabasic dykes. D_1 between D_1 and D_2 can be seen only when the creek is very low. In places it is sill-like. D_1 is 22 ft. wide, and is found directly beneath the "Organ Pipes," but separated from them by Kainozoic grits. D_3 contains nodules of relatively fresh material, the only unaltered mineral being apatite, though abundant augite and olivine can be recognised by the shape of the old crystals and their alteration products. Oblong outlines which may have been plagioclase laths are fairly numerous. The apatite has a vitreous to subresinous lustre. Its shape is remarkable, for it resembles a miniature torpedo. Frequently the crystals are long, but flattened. They can be obtained up to 1¼ in. in length, and down to the smallest needles. All have smooth rounded outlines, but some have small smooth depressions. The smooth outlines and depressions are evidently due to corrosion by the magma. Owing to the extreme brittleness of these crystals, it is difficult to obtain complete specimens. From carefully chosen fragments the S.G. was found to be 3.104, and the P_2O_5 content 40.3 %. A brisk effervescence is set up on dissolving the mineral in hot HCl.

Phenocrysts of olivine, augite, apatite, and felspar were set in a fine groundmass. Of these apatite is the only survivor.

The seven dykes appear to be of the same age, and of the same material, though apatite was found only in D_3. All have the same brownish yellow appearance, the same greasy feeling, the same degree of decomposition, and the same rich iron content, as shown by the iron oxide on the footwalls.

Age of the Dykes.—From their field appearance the basic dykes are all of the same age. The fact that the dykes (D_1 and D_2) are not intrusive into the overlying stratified Kainozoic grits, shows that they are older than either the Newer Basalt or the Kainozoic grits. The fact that they are intrusive into the Silurian sediments, and were not affected by the folding agencies of Lr. Devonian times (16), stamps them as post Lr. Devonian. In one dyke (D_3) a few nodules of partly decomposed rock were found, and this tells us that the dykes are not very ancient. It is, therefore, reasonable to place them with the older basalt, because rocks of this age also occasionally show undecomposed nodules, and it was at this period that vast quantities of basic magma were forced to the surface.

Kainozoic Sediments.

These will be briefly described under the following heads:—

(a) Pre-older-basaltic river conglomerates.
(b) Pre-newer-basaltic grits (Normal "Tertiary Grits.").
(c) Eucalptus leaf beds.
(d) Pre-newer-basaltic river sediments.
(e) Inter-newer-basaltic grits, conglomerates, etc.
(f) Post-newer-basaltic grits, conglomerates and alluvium.

(a) *Pre-older-basaltic river conglomerate.*—This is found in the extreme S.E. of the area, and has been described above.

No fossils were found. Part of this deposit has been altered to quartzite, evidently by the older basalt.

(b) *Pre-newer-basaltic grits and sands.*—These are generally stratified. Near Keilor, about two miles to the south, the grits are stratified, and marine fossils are abundant, but no fossils have been found in the grits of this locality, with the exception of the leaf beds described in the following paragraph. A close study leaves little doubt that all these sandy deposits have been derived from the Bulla granodiorite, the stratified and unstratified deposits apparently merging into one another.

(c) *Eucalyptus Leaf Beds.*—On the left bank of Deep Creek (See Plate XXXII.) a deposit of fine sands and very fine clay bands rests above sands, which in turn rest on the upturned edges of the Silurian sediments. These clay bands are overlain by other sandy layers. The whole deposit is about 30 ft. in thickness, and is covered by more than 100 feet of basalt. The clay bands consist of two sheets about 8 ft. in thickness, light blue resting on dark brown. Both are fossiliferous, but the brown are especially rich. The fossils are leaves of eucalypts, acacias, ferns, and other plants, together with stems and fruits of unrecognised plants. The eucalyptus leaves have been described by Mr. R. Patton (17). From the delicately even strata and the fineness of the clay, the deposit is evidently a lake deposit. The old surface of the Silurian rocks rises to greater heights on all visible sides of the leaf beds, and this, together with the lithological character of the sediments, is strong evidence in favour of their lacustrine origin. There is no evidence as to whether these sands are pre-older-basaltic or post-older-basaltic. The examination of the eucalypt leaves by Mr. R. Patton threw no light on the problem of their age. From their position among the other sandy layers, with which they are conformable, it is probable that they are post-older-basaltic, like the normal Kainozoic grits.

The beds have a decided tilt to the S.E. This may be due to the compression of the loose porous sands by the great overload of new basalt, which here is about 140 ft. in thickness.

(d) *Pre-newer basaltic river sediments.*—These are shown on the map (Plate XXXII.), as areas where plant stems are very abundant. That they are river deposits is shown by their lenticular shape, by the small conglomerate that rests on the valley floor, and by the earthy nature of the matrix. They indicate the sites of pre-newer basaltic valleys.

(e) *Inter-newer basaltic grits and conglomerates.*—The lava flows of the newer basalt in this district are divided into two series—Upper and Lower. This will be explained later. Between the two series is the old soil surface of weathered rock, and in places thick deposits of grit have gravitated from the higher granodiorite in the locality into the valleys corroded in the Lower Series of the newer basalt. These grits, etc., are not stratified. They act as a simple division between the two series of newer basalt. The best occurrences are at points marked F on the map. At Column Gully a heavy conglomerate of quartz and basalt pebbles separates the two series, while in the road cutting north of Bulla an old land surface separates them.

(f) *Post-newer basaltic grits, conglomerate and alluvium.*—All these should be placed as Recent, but as they form only a later stage in the same destructive and constructive process that has been going on right through the Kainozoic, they have been placed under this head. In the neighbourhood of the heart-shaped granodiorite outcrop, unstratified grits can be seen both above and below the newer basalt. The grits have been shed from the hill. This process went on before the older basalt, before the newer basalt, and it is being continued after it. Grit covers or mixes with the basalt soil.

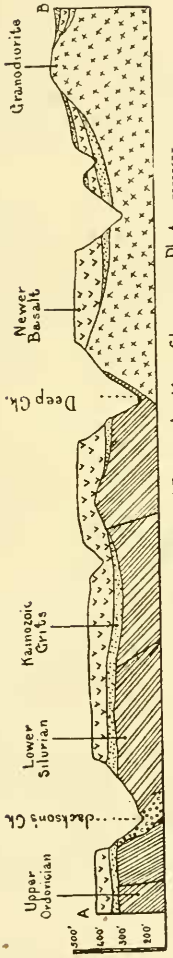
In addition to the massive conglomerates that are now being formed in the stream beds, there are conglomerates of much earlier age formed along the river spurs, especially those of Jackson's Creek, where the deposits are sometimes at least 30 feet in thickness. Generally, they are chiefly rounded quartz and basalt pebbles, and can thus be distinguished from the normal Kainozoic pebble beds which contain no basalt. These deposits have been dropped by the stream as it deepened its bed, but yet the fact should be noted that the great mass of this conglomerate occurs about 100 feet above the present stream level, i.e., when the stream had sunk its bed a little more than 100 feet below the surface. This shows that at that depth the stream cut into an old Kainozoic pebble deposit to the north, and distributed the pebbles on the convex bank of its meanders. The pebbles lower than 100 feet have probably been derived partly from the old pebble beds, and partly from the recent deposits higher up the spurs.

River alluvium, as already described under Physiography, is poorly represented in this area. It is found chiefly on the down-valley side of the spurs, and it usually passes into and overlies a heavy river conglomerate. The best deposit is found on Jackson's Creek, near its junction with Deep Creek.

Newer Basalt.

Newer basalt covers more than nine-tenths of the area mapped. It appears to consist of about seven flows that have come from Red Hill, Sunbury Hill and Bald Hill. This is shown by the contour lines on the military map, by the dominating position of these volcanoes, and by the shape and direction of the vesicles in the basalt. The points of origin of the earlier flows have not been determined. In many places the basalt has a depth of over 300 ft., but it cannot be said from this that each flow is 43 ft. in thickness, for the earlier flows are by far the deepest, since they levelled the old denuded surface. In the neighbourhood of Column Gully excellent columnar structure has been produced in the earlier flows. A description of these columns (14) and the factors producing them (18) may be found in other publications.

Upper and Lower Series.—The various flows of newer basalt in this area are divided into Upper and Lower Series by sandstone bands, river conglomerates, or thick surface soil. The places where a good junction of the Upper and Lower Series can be seen is marked F on the map. That a considerable time interval elapsed between the two series is shown by the denuded surface of the Lower, by its older appearance and more decomposed state, and by the thickness of surface soil on the Lower Series. Generally the thick scree on the valley sides masks the division line of the two series, but excellent junctions are common, especially in the N.W. of the area.



Geological Section along AB on the Map Shown on Plate XXXII.

It might be thought that the Lower Series belongs to the Older Basalt, but there is strong evidence against this:—

(1) The Lower Series rests in places on thick deposits of sand, which appear to be the normal Kainozoic grits.

(2) The river conglomerates between the two series frequently contain basalt pebbles derived from the lower series. These pebbles are only slightly decomposed. If they were older basaltic they would be thoroughly decomposed.

(3) Older basalt, three miles to the E.S.E., is thoroughly decomposed, while the lower series described above is only slightly weathered.

Scoria Cone.—Near the junction of Column Gully and Jackson's Creek is a scoria cone which was almost submerged by the youngest lava flows. A study of the sections shows that at first effusive and explosive eruptions alternated, and then gave place to a prolonged discharge of scoria and agglomerate. The uppermost of the four layers of scoria is still about 100 feet thick. Probably denudation has reduced its thickness. At one point a wall of dense basalt pierces the scoria. It is evidently a blocked up vent, or dyke.

The scoria is of the same age as the "Organ Pipes," and the columns in Column Gully, and, therefore, belongs to the Lower Series of Newer Basalt. At one point on Jackson's Creek scoria overlies and underlies the columnar basalt.

Microscopic Examination of Upper Newer Basalt.—Sections were made of very tough basalt from the small quarry on Deep Creek, north of the Leaf Beds. It proved to be a hypocrystalline rock, in which some glass was present. Large phenocrysts of olivine were set in matrix of fairly coarse labradorite. Augite and magnetite were very abundant, while iddingsite frequently replaced the olivine. The sections gave good examples of ophitic structure, for augite commonly included the labradorite laths. Flow structure was illustrated by the orientation of the labradorites, and the manner in which they "flowed" round the olivines. The rock was a coarse grained basalt.

Porphyritic Basalt.—In the triangle between Redstone Hill, Bulla and the Organ Pipes, there is a peculiar flow of dense porphyritic basalt that belongs to the Upper Series. Near the Redstone Hill, a volcano on Jackson's Creek, it is found resting directly on the sands that separate it from the Lower Series. In several places in Deep Creek and Jackson's Creek it is found in a perfectly fresh state, but above the Organ Pipes it appears in a more weathered and vesicular state. Boulders of this porphyritic basalt in the stream can readily be identified by the smooth light-brown surface spotted with black augite crystals. Under the microscope sections show that the rock contains perfectly fresh plagioclase, augite, and olivine phenocrysts up to ½ in. in diameter, set in a finer paste. The rock closely resembles the Tweed Head basalt of Queensland.

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DESCRIPTION OF PLATES.

PLATE XXXII.

Geological map of the Bulla-Sydenham Area.

PLATE XXXIII.

Fig. 1.—Type of kaolin deposit due to pneumatolysis.

Fig. 2.—Type of kaolin deposit formed by the action of atmospheric water and gases.

Fig. 3.—Meanders of Deep Creek. The heavy line shows the present course of the stream; the dotted line indicates the original course of Deep Creek.

Fig. 4.—Primary and secondary meanders of Jackson's Creek. The heavy line shows the present course of Jackson's Creek, with both primary and secondary meanders, while the dotted line indicates part of the original course of the stream on the surface of the basalt (with primary meanders). The large curves are primary, and are produced by the inequalities in the original land surface, but the small meanders are secondary, and are due to subsequent stream development.

Fig. 5.—This diagram shows how the bed of a stream in the spurred type of entrenched meander moves both horizontally and vertically.

PLATE XXXIV.

Fig. 1.—Photograph of a spurred entrenched meander on Deep Creek. Water-worn pebbles are found along the crest of the spur. The flood plain on the down-valley side of the spur has been caused by the down-valley sweep of the meander. At the point x are the Eucalyptus Leaf Beds.